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AIR QUALITY IN PASSENGER CABINS OF DC-9 AND MD-80 AIRCRAFT

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ABSTRACT

The air quality in the passenger cabins of DC-9 and MD-80 aircraft has been studied on 48 representative flights. A portable air sampling case was used. No observations of health effects were made. The average levels of the components related to environmental tobacco smoke, were for respirable suspended particles 60, 250, 160 and 220 $\mu g/m^3$; for nicotine 5, 41, 21 and 32 $\mu g/m^3$; and for carbon monoxide 0.6, 1.1, 0.8 and 1.1 ppm in Business Non-Smoking, Business Smoking, Tourist Non-Smoking and Tourist Smoking sections respectively. The levels of carbon dioxide and relative humidity were about 1300 ppm and 25 percent in all sections respectively.

INTRODUCTION

Very few studies of air quality in aircraft passenger cabins have been performed due to the technical problems involved. The development of portable air sampling units has made it possible to do studies under normal operating conditions. Previous studies have dealt mainly with the impact of environmental tobacco smoke (ETS), with only limited attention to humidity, temperature, ozone and chemicals not directly related to ETS, such as carbon dioxide and nitrogen oxides. They were reviewed and summarized by Holcomb 1988 (1). He concludes that measurements of the constituents of ETS fail to support claims that exposure levels in aircraft affect adversely the health of non-smoking passengers or crew and that the available scientific evidence does not support the prohibition of smoking on commercial aircraft. Other factors of importance for cabin air quality have also been studied (2,3, 4, 5). The results of those studies show that aircraft cabin air quality is generally similar to indoor air quality, except for particularly low relative humidity, low air pressure and low oxygen partial pressure.

The present study sought to obtain reliable data on air quality on one series of aircraft by analyzing air samples from a large number of Scandinavian Airline System (SAS) flights under various conditions. Besides concentrations of respirable suspended particles (RSP), nicotine and carbon monoxide, which are used as markers of ETS, carbon dioxide concentrations and relative humidity and temperature were used to evaluate cabin air quality. No observations of health effects were made.

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MATERIALS AND METHODS

Study Design

In the various types of DC-9 and MD-80 aircraft that were the subject of this study, there were four sections, business non-smoking (BNS), business smoking (BS), tourist non-smoking (TNS) and tourist smoking (TS), from fore to aft. Forty-eight European flights with a duration of more than one hour were selected. The flights were taken on week-days between September 14 and 30, 1988. The purpose was to obtain a representative sample of flights with respect to weekdays, types of aircraft, and other relevant factors. A summary of the flights is given in Table 1. On average 75% of the seats were occupied by passengers. The percentage was a little less in the DC9-21 aircraft.

Table 1: Number of flights during different conditions

Weekday	Mo:8, Tu:8, We:10, Th:12, Fr:10
Time of dep	Morning (8.00-11.00):13, Noon (11.00-16.00):17, Afternoon (16.00-21.00):18
Aircraft	DC9-21(75 seats):6, DC9-41(110 seats):22, MD-81/83 (133 seats):20
Flight time:	1-2h:33, 2-3h:12, 3h:3

The flights were treated as a random sample in the statistical analysis below. The boundaries between the sections vary between flights and are determined one or two hours before take-off. A random seat was selected for each sampling unit with equal probabilities in each section for a total of four units per flight.

Air sampling, measurements and chemical analysis

Air from the cabin was collected continuosly during the whole flight and its contents of respirable suspended particles (RSP), nicotine, carbon monoxide and carbon dioxide were determined. Barometric pressure, relative humidity (RH) and temperature in the cabin were continuosly monitored. RSP was also recorded continously using a tyndallometer (TRP, tyndallometrically recorded particles).

Other observations of conditions in the cabin were meals served, whether hot or cold, a count of cigarette butts in smoking and non-smoking sections, and a post-flight record of the direction of the gaspar directly above the sampling instruments.

On some occasions a few butts were found in non-smoking sections. In subsequent analyses it was found that excluding the corresponding measurements would affect the results only marginally.

A portable instrument was used, which was designed for integrated sampling and some on-line measurements. The instrument was developed, constructed and tested by the Dutch laboratory TNO. The sampling and monitoring equipment was contained within an ordinary briefcase with a double lid, dimensions 47x34x17 cm. The sampler weighed about 14 kg.

A central sampling tube was situated along the length of the briefcase and contained successively from inlet to outlet:
- a temperature/relative humidity probe (Vaisala type HMP 31UT)
- a tyndallometer for monitoring of the respirable dust concentration (Dräger type Hund TM Digital P)

- a filter holder with a Teflon membrane filter (Millipore, 1 μm) and a cyclone to separate the coarse dust particles from the respirable particles (Casella Ltd)
- a fan with an air flow rate of 100 l/min (Micronel V301 l/M).

The other instruments in the briefcase were:
- a pressure sensor (Micro Switch, Honeywell Division, type 140 PC)
- a vacuum membrane pump (Verder Vleuten, type N 10.AN.E)
- a rechargeable 12 V/9.5 battery (Sonnenschein type Dryfit A200)
- a data logger (Squirrel type Grant 1200).

The sampling pump was connected with:
two XAD-2 adsorption tubes (SKC Inc.) for the collection of nicotine
- a filter holder with a cyclone separator for the collection of samples of respirable particles
- a Tedlar (PVF) sampling bag (Chrompack) for collection of air samples for subsequent measurement of time-weighted average concentrations of CO and CO_2.

The sampling flow rates of the adsorption tubes (1 l/min), filter (1.9 l/min), and the bag (1-2 l/hour) were adjusted by needle valves. The flow rates were measured with two flowmeters located in the outer lid. The plastic bag was situated between the two lids. The data logger monitored the signals from the pressure transducer, the temperature/relative humidity probes, the tyndallometer, and the battery voltage. A Grant Squirrel meter/logger, series 1200, was used to collect data.

During normal operation with the exterior switch in the "on" position, the data logger was programmed to record the respirable particles concentration as measured by the tyndallometer, pressure, temperature, relative humidity and battery voltage once every 5 seconds.

Sampling procedure. Each sampler was placed upright in a seat and secured with a seatbelt, the air intake port of the central sampling tube facing forward and the intake of the XAD tubes facing upward. Thus the air intake was 40 - 50 cm above the upper surface of the seat. All samplers were turned on when the aircraft left the gate and turned off when the aircraft stopped at the gate upon arrival.

A coordinator sat in the last row of the aircraft and was responsible for coordinating such tasks as seat selection, interaction with flight crew, pre-flight checking of ashtrays, completion of an in-flight survey sheet, and collection of cigarette butts. Cigarette butts were collected and identified by location. The counts were noted on a seating plan of the aircraft. The occupied seats were indicated on a second seating plan on the same sheet. The locations of the samplers were indicated on both plans.

Analytical methods. The CO and CO_2 contents in the air sampled in the plastic bag were analysed on the same day at the base station. The CO concentration was measured with a Maihak Unor 6N infrared gas analyzer. The detection was based on absorption of infrared radiation (non-dispersive infrared). The lower detection limit was 0.1 ppm; the range was 0-50ppm. The relative inaccuracy of the CO readings in this study was about 10%, based upon calibrations. The CO_2 concentration was also measured with an instrument based on infrared absorption: a Maihak Sifor 2 Infrarot-Analysator. The range was 0-3000 ppm. The relative inaccuracy of the CO_2 readings was about 5%, based upon calibrations.

The instruments were calibrated each working day. The calibration gases were provided by AGA and Norsk Hydro; the concentrations were 9.8 and 19.6 ppm CO and 986 and 2442 ppm CO_2. Zero set point was determined with pure nitrogen.

Each filter was weighed three times. The averages were used for the calculation of the weight of the collected dust, the respirable suspended particles. The exposed XAD-2 tubes were sealed and stored in a refrigerator until analysis for nicotine. The tubes were analyzed by transferring the XAD resin from the tube to a sample vial in which the nicotine was desorbed with 2.0 ml of ethyl acetate containing 0.01% (v/v) triethyl amine. An aliquot of the desorbed sample was injected into a Hewlett-Packard gas chromatograph with a nitrogen-phosphorous (NPD)-detector. The value determined for blanks, which had not been exposed, was 0.03 µg. The weights of nicotine were corrected for this blank value.

Statistical methods.

On some of the flights one or more of the instruments did not work. The number of missing values are 2 for RSP, 7 for TRP-average and TRP-maximum, 2 for nicotine, 9 for CO, 8 for CO_2 and 3 for humidity. When necessary, these observations were excluded from the analysis.

The mean levels of contaminants were estimated without any model assumptions by using design based estimators. Log-normality was assumed to estimate the variation between seats on different flights. Finally the observed values were explained by using multiple regression. In the statistical tests 5% was used as the level of significance.

Every seat in each section on each flight had the same probability to be drawn. This means that the seats in the smaller sections represent fewer passengers than those in larger sections. When computing averages over the whole plane, the observations were weighted with the proportion of passengers in the sections. The same type of weighting was also used in computing the averages for the same section on different flights. This means that the expected exposure of a typical passenger in that section was estimated.

All means were then estimated by the Horvitz-Thompson estimator (6, 7). The standard deviation for the section levels was computed using standard formulae for ratio estimates. The expected levels discussed above were computed without any model assumptions. For further analysis a statistical model is, however, needed. The standard model for such measurements is log-normal. The model was found to be acceptable by plotting the cumulative distributions of the observations on log-normal probability paper.

Using the assumption of a log-normal distribution the variations between passengers were calculated. The 50th percentile was estimated by the weighted geometric mean $\exp(m^*_{LN})$, where

$$m^*_{LN} = \frac{\Sigma \ln x_i/\pi_i}{\Sigma 1/\pi_i} .$$

The 5th and 95th percentiles were then estimated as

$$\exp(m^*_{LN} \pm 1.96\, s_{LN}) \text{ where } \quad s^2_{LN} = \frac{\Sigma (\ln x_i)^2/\pi_i}{\Sigma 1/\pi_i} - m^{*2}_{LN}.$$

RESULTS

Levels of air components

The mean temperatures were 23.9, 23.8, 23.6 and 23.4°C in BNS, BS, TNS and TS, respectively. There were large variations around these means. The lowest observed mean temperature was 20.1°C and the highest 28.3°C. The air pressure started around 100 kPa and went down to between 75 and 80 kPa when the plane was in the air. The mean pressure is highly related to length of flight.

The rest of this section concentrates on results concerning air components, RSP, TRP, nicotine, CO, CO_2 and humidity.

The averages for the DC9-21 are lower than those for the DC9-41 and MD-80 with respect to almost all the variables (see Table 2). Although the differences are statistically significant, they can often be explained by other background variables. The differences in humidity and carbon dioxide, however, still remain.

The differences between different sections shown in Table 3 are larger than those between different types of aircraft. The concentrations of ETS-components (RSP, TRP, nicotine and CO) are lower in BNS than in the other sections. This difference is statistically significant. The levels of measured ETS-components in TNS is lower than in the smoking sections. The last difference is partly a result of the weighting procedure. The unweighted differences between TNS and the smoking sections were not statistically significant for CO_2 and TRP-average, and significant at the 5% level for the other ETS-components. The unweighted averages of CO_2 are increasing from the first (BNS) to the last (TS) section of the aircraft.

The levels of components measured were higher at the window seats than at the aisle seats. The differences were small, but consistent for nicotine, RSP and CO_2. The differences may depend on the number and location of occupied seats in the aircraft.

There are no important differences between the days of the week. Even though a few differences were statistically significant for some sections, this is probably only a result of the large number of comparisons. There were, however, clear differences according to the time of day. There were higher levels of measured ETS-components in the afternoon than in the morning. There were also differences according to the length of flight. The longer the flight the lower the measured ETS-components in the air.

Table 2: Average level of air components by type of aircraft

	Aircraft type					
	DC9-21		DC9-41		MD-80	
RSP ($\mu g/m^3$)	110	(14)	130	(10)	150	(16)
TRP Average reading (mV)	0.8	(0.09)	1.2	(0.08)	1.2	(0.11)
TRP Maximum reading (mV)	12	(3.6)	13	(1.5)	9	(1.0)
Nicotine ($\mu g/m^3$)	13	(2.1)	21	(1.7)	19	(2.0)
Concentration of CO (ppm)	0.7	(0.06)	0.8	(0.006)	0.9	(0.09)
Concentration of CO_2 (ppm)	990	(74)	1300	(60)	1310	(53)
Mean Relative Humidity (%)	21	(1)	25	(0.8)	25	(0.9)

Cell content: - Weighted mean value, all sections
- Standard error for mean value in parenthesis

Table 3: Average level of air components by section

	Class and section							
	BNS		BS		TNS		TS	
RSP ($\mu g/m^3$)	60	(7)	250	(18)	160	(15)	220	(21)
TRP Average reading (mV)	0.6	(0.1)	1.9	(0.1)	1.3	(0.1)	1.7	(0.2)
TRP Maximum reading (mV)	4	(0.8)	29	(4.4)	7	(0.8)	18	(3.2)
Nicotine ($\mu g/m^3$)	5	(0.9)	41	(3.6)	21	(2.5)	32	(3.5)
Concentration of CO (ppm)	0.6	(0.06)	1.1	(0.08)	0.8	(0.07)	1.1	(0.11)
Concentration of CO_2 (ppm)	1310	(41)	1310	(42)	1270	(36)	1430	(36)
Mean Relative Humidity (%)	25	(0.7)	25	(0.8)	25	(0.6)	25	(1.0)

Seat arrangement

Cell content: - Weighted mean value, all flights
- Standard error for mean value in parenthesis

Table 4: Ranges in the levels of air components between flights - Business Non-Smoking (BNS), Business Smoking (BS), Tourist Non-Smoking (TNS) and Tourist Smoking (TS).

	BNS		BS		TNS		TS	
	5%	95%	5%	95%	5%	95%	5%	95%
RSP ($\mu g/m^3$)	12	180	93	540	50	400	65	560
TRP-Average	0.1	2.0	0.5	5.1	0.4	3.6	0.3	5.5
TRP-Maximum	0.6	14	4	110	1.8	20	2.3	69
Nicotine ($\mu g/m^3$)	0.8	17	13	98	4.8	62.1	15	98
Concentration of CO (ppm)	0.1	2.2	0.4	2.7	0.3	2.1	0.4	2.5
Concentration of CO_2 (ppm)	900	1840	850	1930	860	1810	1020	1950
Mean Relative Humidity (%)	17	34	16	36	17	34	15	38

This table shows estimated quantities. For example 5% of the passengers in BNS were exposed to less than 12 $\mu g/m^3$ RSP, and 95% of the passengers in the same section were exposed to less than 180 $\mu g/m^3$ RSP.

The number of butts per passenger per hour was 1.15 in BS and 0.90 in TS. There were no statistically significant differences between different lengths of flight and between different times of departure in the number of butts, per passenger per hour.

It is not only the mean level of components that is interesting. Some passengers are exposed to higher levels and some to lower levels. These variations are due to variations between flights but also between seats in the same sections. A passenger near a smoker will receive more smoke than one whose neighbours are non-smokers.

In Table 4 the values are given below which 5% and 95% of the passengers are exposed. These estimates are based on the assumption of log-normal distributions. The largest proportional variations are found for ETS-components in BNS. For those variables it is not unusual to find a level four times as high as the average given in Table 3. These estimates are, of course, subject to sampling errors.

Regression analyses

In order to explain the measurements by background variables we made several stepwise regression analyses. We tried to explain the values by the following variables: class, section, seat location, place of departure, time of departure, aircraft type, flight time, number of seats in section and in flight, number of passengers in section and in flight, number of butts in section and in flight, number of butts per passenger, butts per seat, passenger per seat.

A common trait was that the measurements in the forward part of the aircraft were explained better by variables per section and in the aft by variables in the whole aircraft. For example, relative humidity in BNS was explained by flight length and the number of passengers per seat in BNS, while the humidity in TNS was explained by flight length and the number of passengers per seat in the whole aircraft. Those variables explained about 50% of the variation.

A typical equation is the following for TNS

$$\log(\text{humidity}) = 5.1 - 0.4 \log(\text{time}) + 0.2 \log \frac{\text{passengers}}{\text{seats in aircraft}}$$

The smoking-related variables such as nicotine and different dust variables were best explained in BNS by the distance to the nearest smoking section. The decrease with distance was quite rapid for nicotine and slightly less rapid for the dust variables.

In TNS the picture is more difficult to describe. For nicotine the distance to the nearest BS row was most important. The dust variables were influenced from both ends of the section. Time of departure, length of flight, and number of passengers per flight also appeared to have had some influence.

The results of the explanatory regressions are summarized in Table 5. All variables having a statistically significant effect in at least two sections have been included in the table.

Table 5: Factors explaining air quality levels

	length of flight	time of departure	number of pass.	number of butts	distance to smoking section	explained variance %
Nic	decr	incr		incr	decr	35-55
RSP	decr	incr		incr	decr	30-70
TRP aver	decr	incr		incr		20-55
TRP max	decr	incr			decr	0-50
CO	decr	incr		incr		0-50
CO2	decr	incr	incr			50-80
Hum	decr	incr	incr			30-60

In the non-smoking sections these analyses explained more than 50% of the variation for nicotine. In TNS they also explained a large part of the variation in the other smoking-related variables. In smoking sections, however, only a small portion could be explained. The exact location of the smokers and the butts have not been used to explain the variation. In the smoking sections this is an important source of variation.

It appears that nicotine does not spread as much as the dust variables (RSP and TRP). TS and TNS are more influenced by flight variables than BS and BNS. This suggests that there is a slight drift backwards of the air.

The residuals were computed, i.e. those parts of the measurements that could not be explained by background variables. Correlations between the residuals were then derived. There were practically no correlations left, which probably means that the remaining parts are due to measurement error or the random location of the TNO cases.

DISCUSSION

The present study is to our knowledge the most comprehensive examination of aircraft cabin air quality performed thus far. The number of flights is large, as well as the number of variables studied. On the other hand, only one family of aircraft has been included. Accordingly, the differences between the results in the present study and those of other studies (see 1) could be due to the extent of the study, different methodologies, different smoking habits, or different aircraft. The last seems the most plausible explanation, particularly when this study is compared with those performed aboard wide-body aircraft with different ventilation systems (8). But any comparison should be made with caution, because, as this study confirms, many factors may affect aircraft cabin air quality.

The air quality in passenger cabins is of importance to the comfort, health and wellbeing of passengers and flight attendants during flight. Therefore it is necessary to study the air quality by analyzing the air content and evaluating the possibly elicited health effects at the concentrations found. The air quality could then be judged either by comparing the values obtained with relevant standards for indoor air or with values from air in different indoor locations including aircraft cabins or by evaluating the possible health effects at the estimated exposure to the components in the cabin air.

In the present study no observations of health effects have been performed. Thus the evaluation of the air quality in the passenger cabin will be based mainly upon comparison with standards and the air quality in other indoor locations.

The effect of ventilation on air quality.

The ventilation and air-conditioning systems of the studied aircraft are all of the same basic design. The recirculation system is only installed in the MD-80s. Two identical systems normally operate in parallel. The left system operates from the left main engine compressor bleed and the right system operates from the right engine compressor bleed. A flow control valve is installed at the inlet to each system and automatically regulates the flow. The flows delivered by both systems for each type of aircraft are given in Table 6. It also gives the volume of the passengers' compartment. Two water separators, one in the outlet of each system, remove excessive entrained moisture from the air and prevent discharges of water from cold air outlets. Coalescer bags fitted in water separators are made from Dacron felt.

Table 6: Air flows

Model	Pass.cab. air flow m^3/h	Max. number seats	Air flow m^3/h per seat	Estim.pass. cabin vol. m^3 *	Theoretically calculated air change h^{-1} (ACH)
DC9-21	2863	75	38.2	87.4	32.8
DC9-41	3664	110	33.3	112	32.8
MD80	4473 **	133	33.6	159	21.6 **

* based on data from Douglas and not allowing for the rear fuselage taper (less than 6 m^3)

** 3435 fresh and 1038 recirculated. ACH rate for MD80 based on fresh air only.

Temperature of the air is automatically controlled in the passenger cabin. The MD-80 passenger air recirculation system increases the air flow by approximately 30% (quoted as a percentage of the fresh air).

The ventilation system is designed to distribute well conditioned air equally to all passengers. On the pressure side the main duct has a number of dropper ducts, each serving about 4 window positions, in order to give the same flow along the slots below the bins. Orifices in the droppers are also used to balance the inflow. Similarly, there are cusps inside the outflow grills with holes, some of which may be plugged with "cusp plugs". These have orifices of various sizes to balance the outflow along the cabin. Typically more cusp plugs are used aft to eliminate backward drift. Care in maintenance of grills and cusp holes is essential. The idea of the arrangement with the orifices in the droppers and the cusp plugs is that, by changing both inlet and outlet all along the cabin length, air can be distributed in the manner required.

All the sampling in this study was made with the ventilation as normally operated. The downward velocity averaged about 1-2 cm per second and the inflow rate of the air was much higher. Velocities in different points vary a great deal and it is obvious that movement of people and goods in the cabin easily causes air movements with higher velocity than the mean downward velocity. The system sought to move the air, as far as possible, at a right angle to the length of the cabin from the discharge slots to the slots at floor level. However, there seems to have

been some backward drift, possibly due to the discharge of air being at the aft end of the aircraft and the difficulty of getting an equalised underpressure in the discharge channel under the cabin floor. It is possible that if the air discharge in the aft part of the cabin is decreased by putting smaller orifices in the cusps of this section in order to decrease the backward drift of air in the cabin, this will tend to increase the concentrations of, for example, RSP and nicotine in the aft sections of the cabin.

When smoking begins the concentrations of ETS related components increase gradually to an equilibrium value. With the high ACH in the aircraft, this equilibrium is reached fairly quickly.

There is a correlation, although weak, between the number of cigarette butts and the concentration of nicotine at the seats in the BS and TS sections of the DC9-41s and in the BS section of the MD-80 but not in the TS section of the MD-80. One reason for the weakness of the correlation may be the fact that the sections cover different numbers of rows and then receive a different amount of air flow, since the air flow through the inlet and discharge slots is proportional to the length of the section, that is to the number of rows. The correlations confirm that the ventilation has some effect transversal to the length of the aircraft. The turbulence of the air in the cabin and the distribution lengthwise and mainly backwards seem, however to be considerable.

Looking at the measured values in detail, there are single values that are extremely low or high with respect to, for example, nicotine. This may suggest that the effects of the ventilation are occasionally blocked off in some way. Smoking in non-smoking sections may be one reason for odd values. In addition, concentrated puffs of cigarette smoke may also have occasionally reached the instrument.

The fairly high CO_2-values may indicate that the air flows, which have not been measured, are lower than those intended. It is difficult at present to assess the efficiency of the ventilation system. Some flows may have been shortcircuited and there may have been disturbances in the operation. The distribution of air over the seats seems to be an important point to investigate if improvements are sought. The study confirms the need for proper trimming and maintenance of the ventilation system.

Evaluation of the air quality.

There are few standards for aircraft cabin air and none for ETS overall. The closest one can get is to compare the values obtained in this study with any standards (see Table 7.). There are official standards for nicotine, carbon monoxide and carbon dioxide. It can be seen that the nicotine concentrations found in the present study are roughly one-tenth of the standard for the working environment set by OSHA. The concentration of carbon monoxide is also about one-tenth of the standard for general indoor air and even less for the working environment. The values for carbon dioxide are between a fifth and a fourth of the standard for the working environment, but close to or sometimes even above what has been tentatively proposed in Japan. It has been recommended that relative humidity should be between 30 and 70%. There is an OSHA workplace standard of 5000 $\mu g/m^3$ for respirable particles. But there is no standard for RSP resulting from ETS.

CO_2 ra...
and
ACH

Table 7: Air quality standards

	Value	Time period	Source
INDOOR AIR IN GENERAL			
Nicotine	500 $\mu g/m^3$	8 hrs	OSHA US
Carbon monoxide	50 ppm	8 hrs	OSHA US
	35 ppm	8 hrs	ASS SWEDEN
	35 ppm	1 hr	EPA US
	9 ppm	8 hrs	EPA US, WHO
Carbon dioxide	5000 ppm	8 hrs	OSHA US
	1000 ppm	8 hrs	ASHRAE, JAPAN
AIRLINE CABIN AIR			
Carbon monoxide	50 ppm		FAA US
Carbon dioxide	30000 ppm		FAA US

OSHA - Occupational Safety and Health Administration
ASS - Workers Protection Board
EPA - Environmental Protection Agency
ASHRAE - American Society of Heating, Refrigeration and Air Conditioning Engineers
FAA - Federal Aviation Administration

From this comparison it appears that the quality of the aircraft cabin air in the present study is satisfactory and better for factors related to ETS - nicotine and carbon monoxide - than for carbon dioxide and relative humidity.

There are several studies of indoor air quality in which markers of ETS such as nicotine, RSP and carbon monoxide, have been measured together with carbon dioxide. Areas where smoking is allowed have been compared with areas where smoking has been prohibited (9), offices have been compared with cafeterias (10) and the indoor air quality has been related to different activities (11). Some ETS components, mainly nicotine, have been measured in various locations (12, 13) including aircraft (12, 14, 15, 8). The results of these studies are quite variable, probably because different techniques and methods have been used. However, there are consistently lower concentrations of the ETS-related factors in non-smoking areas than in smoking areas, e.g. nicotine varies between 0.8 and 8 $\mu g/m^3$ air in non-smoking areas and between 4.8 and 99.2 $\mu g/m^3$ air when smoking is allowed. RSP and carbon monoxide show similar patterns.

When comparing the results of the present study with the above mentioned studies it can be concluded that nicotine and RSP values are within the range of those of earlier studies, while carbon monoxide is slightly lower and carbon dioxide slightly higher.

It is difficult to evaluate the possible health effects of the cabin air studied. It is not homogeneous and the concentrations of the components vary. Most of the reported concentrations are mean values over the whole flight, and the air sampling was not done in the respiratory zone or close to the eye. Thus the analyzed values cannot be considered a complete and precise description of the exposure of persons in the aircraft passenger cabin. There are particular uncertainties with respect to cabin crew. The degree of exposure could have been modified by several factors; therefore, individual assessment would be desirable. The variations in

the absolute concentrations over time are important for any irritation, while the average exposure during the whole flight is important for possible long-term effects.

There is considerable scientific controversy about the health effects of ETS, and no unanimity about how to estimate exposures to the complex ETS mixture. In the present study nicotine, respirable suspended particles and carbon monoxide were chosen as indicators, because, even if imperfect, they are probably the most reliable measures, while carbon dioxide, temperature and relative humidity were selected as indicators of general air quality.

It is important to note that although nicotine and carbon monoxide are major components of ETS, an evaluation of the possible health effects of ETS cannot be based simply upon what is known about the toxicity of these two components. Furthermore, the composition and quantity of ETS derived from cigarettes is variable. Hundreds of compounds have been identified in ETS and several of them have been shown to have various degrees of toxicity.

The degree and frequency of health effects, if any, for any individual could have been modified by each such individual's particular situation and history. Since it is reasonable to assume that the exposure to ETS in smokers is rather small compared to the exposure from active smoking, this evaluation considers only non-smokers, insofar as it relates to ETS. The evaluation will be divided into acute effects and long-term effects.

Any acute effects that may have occurred during the studied flights would mainly have consisted of local irritation of eyes and mucous membranes in the mouth and respiratory tracts, effects on the respiratory and cardiovascular function, and annoyance effects because of odour.

Local irritation varies among individuals, but could seem very unpleasant to sensitive people. Objectively, the irritation would have been slight or very slight for most passengers, at least in the smoking sections and in the TNS close to the smoking sections for non-smokers and flight attendants, if it occurred (16). Contact lens wearers are particularly vulnerable to eye irritation (17). Factors other than ETS, e.g. temperature and humidity, can influence local irritation. The low humidity recorded in this study could have had a clear contributory effect for local irritation (18, 19). Low humidity in itself is known to cause symptoms in the eyes and upper respiratory tract. Ozone and other chemicals not related to ETS may also contribute to local irritation of the eyes and respiratory tract.

Any effects on the respiratory function could have ranged from easily and objectively observed effects, such as coughing or changes in respiratory function parameters, to pain or other subjective symptoms. Of special interest and concern are the possible occurrence of asthmatic attacks or similar serious impairments of respiration due to air components such as ETS. The possible effects of ETS on asthmatics have been addressed in many papers (20, 21, 22, 23). It seems fair to conclude that ETS has only minor effects on the respiration of asthmatics. In particularly sensitive individuals or in severe cases, effects on the respiration cannot be completely ruled out but any effects would have been indirectly elicited by the annoyance, odour or other signs of tobacco smoking. However, other factors, such as lowered oxygen pressure, increased temperature and chemicals from other sources, may equally be causes of any such respiratory dysfunctions.

Any effects on the cardiovascular system would have been mostly unnoticed in healthy individuals, because there are no known direct effects of ETS on the cardiovascular system beyond the formation of carboxyhemoglobin. The latter is so minimal that it will not affect the cardiovascular function. People with compromised cardiovascular conditions might have experienced pain or other symptoms during flight. However, these symptoms would be more likely to have been caused by low oxygen pressure, high temperature, or factors other than ETS.

Long-term health effects normally need long-term exposure. Thus it is most unlikely that any long-term effects would have been initiated due to the exposure during the present study.

Any such effects could only be a possibility for persons flying fairly frequently. That is true mainly for cabin crew and a small group of frequent travellers. However, the exposure time to ETS during flying for these individuals is still only a small fraction of their total lives. For most other passengers, flying time is less than a thousandth of their lives, proportionally reducing the possible long-term exposure. Furthermore, intermittent exposures with intervals for recovery favourably counteract most long-term health effects.

Exposure time for flight crew? Any study?

Some but not all epidemiological studies have shown a higher incidence of lung cancer among individuals who have been married to smokers. Whether ETS is a causal factor of lung cancer is a controversial issue, which is outside the scope of this study.

Since it is unlikely that passengers or cabin crew would have experienced significant health effects due to the airline cabin air studied in this investigation, the air quality could be considered acceptable. If, however, airline cabin air quality were judged according to comfort and well-being, it is questionable if it could be regarded as satisfactory. First the humidity is far below what is considered comfortable. Second, the carbon dioxide is close to or slightly above what is recommended in a proposed ASHRAE and Japanese standard. Third, it cannot be excluded that the levels of ETS could create some discomfort to some passengers seated near to smokers. The latter could be studied by investigating reactions of individuals during flights.

CONCLUSIONS

An effective ventilation system is essential for cabin air quality. The concentrations of tobacco smoke-related compounds (ETS-components) were higher in the smoking sections than in the non-smoking sections, but concentrations of those compounds were also found in non-smoking sections, particularly the tourist non-smoking sections. Instead of a row-by-row elimination, the air contaminants seem in part to drift backwards in the cabin. The relatively high concentrations of carbon dioxide are another indication that the ventilation system was not replacing the air as quickly as is necessary to maintain air quality. Although there are no standards for ETS in aircraft cabin air, comparisons with other official standards can be used to evaluate air quality in passenger cabins. The nicotine concentrations found are roughly one-tenth of the standard for the working environment, the carbon monoxide concentrations about one-tenth of the standard for general indoor air, while carbon dioxide concentrations are about one-fourth of the standard for the working environment but slightly above what has been tentatively proposed.

The total exposure to cabin air ETS among the passengers is rather small and insignificant in comparison to total life exposure to air pollution. Although the exposure of the cabin crew is more difficult to estimate, the total exposure per flight is reasonably correlated to the weighted mean averages found and the overall total exposure per day, based in part upon the number of flying hours for each individual.

Some passengers and cabin crew might have experienced eye and upper respiratory tract irritation and annoyance at the highest exposure levels recorded. These effects could have been potentiated by the low humidity, high temperature and high carbon dioxide levels found. More pronounced health threatening effects, such as asthmatic attacks in passengers with such a compromising medical condition, are most unlikely. Long-term effects are not likely to have been elicited by exposure to concentrations experienced during the studied flights, mainly because the exposure is insignificant compared to the total life exposure to indoor air pollution. Any possible long-term health effects were most likely insignificant in passengers and cabin crew with or without compromising medical conditions.

When using the present study to estimate risks of possible health effects for passengers and cabin crew due to aircraft cabin air, the expected total exposure time must be taken into account. Since even a very frequent traveller is exposed during only a small fraction of his/her time, airline cabin air most likely contributes insignificantly to the total health effects of indoor air pollution. Aircraft cabin air does not have higher levels of contamination than many other indoor locations.

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